COOLING WITH SUNSHADES

GRADE LEVEL

9 - 12

DURATION

2-3 45-minute classes

ESSENTIAL QUESTION

How can passive cooling methods keep an object at a comfortable temperature?

LESSON OVERVIEW

LESSON SUMMARY

In this lesson, students discuss some of the basic properties of temperature and heat, and learn different ways in which heat can affect substances. As an example, the students consider sunlight and how it can heat objects on Earth. They construct a simple device based on the phase change of water from ice to liquid to investigate the effectiveness of different shading materials, as well as the cost-effectiveness of different shade designs. They discuss how MESSENGER uses a sunshade to keep comfortable at Mercury's distance from the Sun.

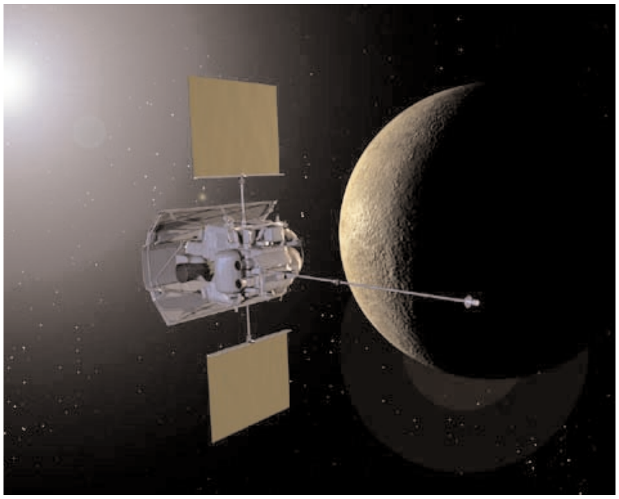

Figure 1. The MESSENGER spacecraft is equipped with a sunshade that is facing the Sun at all times to keep the spacecraft components at a safe temperature. (Picture credit: http://messenger.jhuapl.edu/press/spacecraft_img.html)

OBJECTIVES

Students will be able to:

- ▲ Construct a simple device to measure the effectiveness of different shielding materials against sunlight.
- ▲ Explain how heat relates to the motion of atoms and molecules of a substance.
- ▲ Describe how heat can be transmitted from one place to another.
- ▲ Explain how sunlight arriving on Earth interacts with matter.
- ▲ Describe how MESSENGER is protected by a simple sunshade in the hot Mercurian environment.

Concepts

- ▲ Radiation from the Sun is the main source of energy on Earth. It heats the Earth to a temperature at which life is sustainable.
- ▲ Temperature describes the average internal energy of the atoms and molecules of which the substance is composed; it is also a measure of the amount of disorder in the substance.
- ▲ Heat can be transmitted via conduction, convection, and radiation.
- ▲ Heat interacting with material causes it to change temperature, size, or physical state (phase).
- ▲ When a substance changes phase, its temperature remains the same until all of it has changed its phase: the temperature of ice water can rise only after all the ice has melted.
- ▲ When designing a scientific experiment, it is important to consider possible sources of errors and improve the basic design to reduce these errors.
- ▲ In designing devices to be used in practical applications, it is important to take into consideration the cost-effectiveness of the device: the efficiency of the device in solving the problem compared with its total cost.

MESSENGER Mission Connection

MESSENGER uses passive cooling methods such as a sunshade to make sure the spacecraft components can operate in safe temperatures.

> **WARNING**
>
> **Do *not* look directly at the Sun!**
>
> This lesson is about the Sun and sunlight, but be sure to remind students frequently ***never* to look directly at the Sun!** Looking for even a few seconds can cause permanent damage to the eyes, and longer exposure can cause blindness. Note that sunglasses do *not* provide an adequate safeguard against looking directly at the Sun.

Standards & Benchmarks

National Science Education Standards

Standard B5 Conservation of energy and increase in disorder

- ▲ Heat consists of random motion and the vibrations of atoms, molecules, and ions. The higher the temperature, the greater the atomic or molecular motion.
- ▲ Everything tends to become less organized and less orderly over time. Thus, in all energy transfers, the overall effect is that the energy is spread out uniformly. Examples are the transfer of energy from hotter to cooler objects by conduction, radiation, or convection and the warming of our surroundings when we burn fuels.

Related Standards

Standard E1 Abilities of technological design

- ▲ Identify a problem or design an opportunity: Students should be able to identify new problems or needs and to change and improve current technological designs.
- ▲ Propose designs and choose between alternative solutions: Students should demonstrate thoughtful planning for a piece of technology or technique. Students should be introduced to the roles of models and simulations in these processes.

Standard F6 Science and technology in local, national, and global challenges

- ▲ Individuals and society must decide on proposals involving new research and the introduction of new technologies into society. Decisions involve assessment of alternatives, risks, costs, and benefits and consideration of who benefits and who suffers, who pays and gains, and what the risks are and who bears them. Students should understand the appropriateness and value of basic questions — "What can happen?"—"What are the odds?"—and "How do scientists and engineers know what will happen?"

American Association for the Advancement of Science, Project 2061

Benchmark 4 E/1: Whenever the amount of energy in one place or form diminishes, the amount in other places or forms increases by the same amount.

Benchmark 4 E/2: Heat energy in a material consists of the disordered motions of its atoms or molecules. In any interactions of atoms or molecules, the statistical odds are that they will end up with less order than they began – that is, with the heat energy spread out more evenly. With huge numbers of atoms and molecules, the greater disorder is almost certain.

Benchmark 8 B/3: Scientific research identifies new materials and new uses of known materials.

SCIENCE OVERVIEW

One of the easiest ways to keep materials cool in sunlight is to put them in shade. People in warm climates are very familiar with the idea, as it is a simple and inexpensive way to keep items in a cool environment when active refrigeration is not possible. Similar ideas based on observing the properties of light, heat, and shadows can be used in developing space missions exploring environments with different temperatures. On a planetary scale, we are familiar with being shaded from the Sun at night in our daily cycle. On Earth, our dense atmosphere keeps the variations between daytime and night-time temperatures moderate, but on planets and moons that have no atmosphere, or only a very tenuous atmosphere, the variations may be extreme.

Temperature and Heat

An object's temperature is a measurement that describes the level of motion and vibration in the atoms and molecules of which it is composed (that is, the internal energy of the atoms and molecules). The higher the temperature of the object, the more vigorously its atoms and molecules move around and bounce off each other, and the more disorderly is their motion. This means that heat flowing into an object increases the internal energy and disorder in that object, while heat flowing out of it decreases its internal energy and disorder. For example, the water molecules in a snowflake are arranged in an orderly pattern. If you hold a snowflake in your hand, it will melt and become a drop of water. While it melts, the orderly pattern of the snowflake is changed into the more disorderly form of liquid water.

Thermodynamics

The science of thermodynamics studies the relationships between various forms of energy, such as heat and mechanical work. There are three basic laws of thermodynamics:

1) Energy may change form, but it is never created or destroyed ("conservation of energy"). For example, heat and chemical energy can be changed into mechanical energy by steam turbines and by automobile gasoline engines.

2) Heat energy flows from hotter to colder substances unless work is done.

3) There is a theoretical temperature at which matter would have the least possible internal energy and no disorder. However, it is impossible to reduce the temperature of any system to this absolute zero, 0 K (-273°C, -459°F).

Transmitting Heat

If you hold a snowflake in your hand, it will melt because the heat from your hand travels to the snowflake and causes its temperature to rise. In general, heat passes from one substance or object to another by:

1) Conduction

- Heat moves through material without any of the material moving.
- E.g., the tip of a metal pitchfork placed in a fire: vibration of atoms is transmitted from the tip throughout the pitchfork, but none of the atoms move from the tip to other parts of the pitchfork.

2) Convection

- Heated material moves and carries heat with it.
- E.g., heating water in a pot on a stove: hot liquid from the bottom of the pot rises up, while cold water sinks down to be heated.

3) Radiation

- Heat is transmitted via electromagnetic radiation, either through a medium (such as air) or without need for material (e.g., through space).
- E.g., infrared rays, visible sunlight.

What Is Electromagnetic Radiation?

Weather forecasters often show temperature maps of the United States based on the temperature measurements in different parts of the country that day. The maps are created by assigning each temperature a color, and then filling the map with colors corresponding to the temperatures measured at each location. A map created this way shows the temperature field of the United States on that particular day. The temperature field covering the United States, in this sense, is a description of the temperatures at every location across the country.

In a similar fashion, the universe can be thought of as being permeated by an electric field. All electrically charged particles (such as electrons) have a region of space around them where they influence the behavior of other charged particles wandering there. This region can be described as an electric field around the particle. Just as temperatures in different parts of the country create the temperature field of the United States, the electric charges in the universe can be thought of as creating an electric field permeating the whole universe. Magnetic objects behave in a similar fashion: every magnetic object creates a magnetic field around it, and their collective magnetic field permeates the universe.

Most things in the universe tend to move around, and electric charges are rarely an exception. If the velocity of an electric charge changes (that is, it accelerates or decelerates), it creates a disturbance in the electric and magnetic fields permeating the universe. These disturbances move across the universe as waves in the "fabric" of the electric and magnetic fields. The waves also carry energy from the disturbance with them, in a similar way that the energy of the wind striking a flag is carried across the fabric by the waving of the flag. The waves carrying the energy of the disturbance across the universe are characterized by their wavelength, which measures the distance between two consecutive wave crests.

A familiar example of this kind of wave is visible light. Different colors of visible light have slightly different wavelengths, and there are waves which have

much higher and shorter wavelengths than the light that humans can see. Together, the waves of all different wavelengths are called electromagnetic radiation, and the whole array of different kinds of light, arranged according to their wavelength, is called the electromagnetic spectrum. Electromagnetic radiation travels at the speed of light (300,000 km/s or 186,000 miles/s in a vacuum such as space).
(See Figure 2.)

Electromagnetic radiation is not the same as "heat" – it is a way to transmit energy from a heat source as radiation. The energy can then be felt as heat when it interacts with matter (e.g., feeling warm sunlight on our skin). Energy transmitted this way can travel through a medium (e.g., sunlight traveling through the Earth's atmosphere) but it can also travel through a vacuum in space. In both cases, the transferred energy creates heat in objects that absorb the radiation. We usually associate heat with infrared radiation, since our bodies are warm and therefore emit radiation in infrared wavelengths. (Remember that our bodies do not emit visible light; we see each other because of light reflected by our bodies, but originally emitted by the Sun or another light source.) Hot objects (such as the Sun) emit energy also in other wavelengths, including visible light. The energy of sunlight is carried through space by electromagnetic radiation of all kinds.

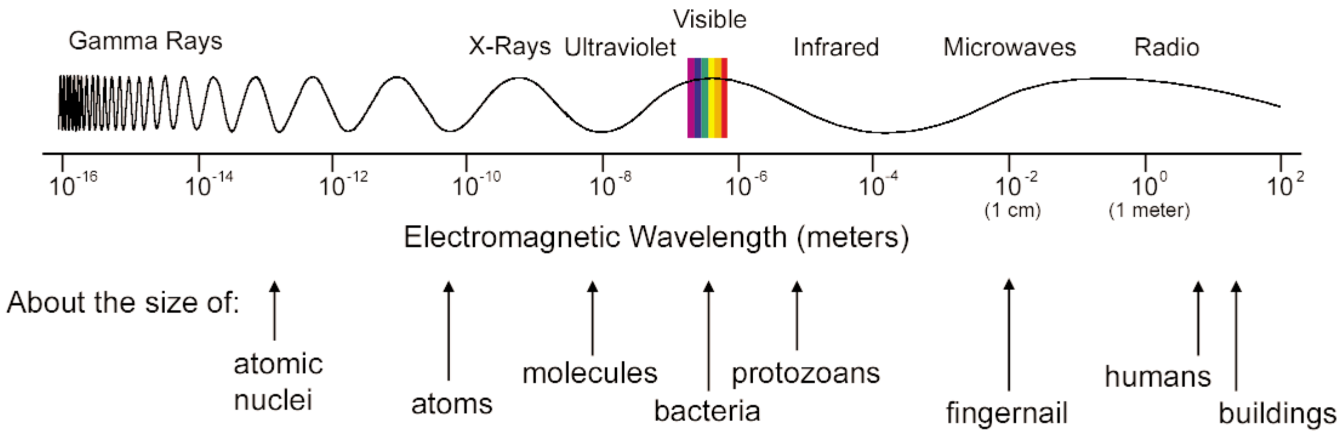

Figure 2: The electromagnetic spectrum. In the picture, different parts of the spectrum are shown as one continuous wave. In reality, a given electromagnetic wave has one particular wavelength. The continuous wave in the picture above is used to better illustrate the difference between wavelengths from one part of the spectrum to another.

How Heat Changes a Substance

There are three basic ways in which heat can change materials:

1) Change in temperature
- The internal energy of the atoms and molecules of the material increases.
- This is the most common result of heat interacting with matter.
- The amount of heat needed to raise the temperature of one gram of a substance one degree Celsius is called the specific heat capacity (or just specific heat) of the substance.

2) Change in size
- Since the motion of the atoms and molecules in the substance increases when heat flows into it, the atoms and molecules need more space and the substance expands in most cases.
- In contrast, when heat flows out of a substance, the atoms and molecules move more slowly and require less space; the substance contracts in most cases.
- All gases and most liquids and solids expand when heated. An important exception is water, which contracts when its temperature rises from 0˚C (32˚F) to 4˚C (39˚F), and only then starts expanding as it is heated. The same is also true when water changes phase from solid to liquid: water contracts when heated from ice to liquid. This property is due to water's rigid crystal structure in the solid state (ice).
- The change in size is the basis for bulb-type thermometers, among other things.
- This effect must be taken into account when building bridges, buildings, and other structures, so that the materials will be able to expand and contract without causing severe problems.

3) Changes in the physical state (phase)
- Melting: heat causes a substance to change from solid to liquid.
- Freezing: loss of heat causes a substance to change from liquid to solid.
- Boiling: heat causes a substance to change from liquid to gas.
- Condensation: loss of heat causes a substance to change from gas to liquid.
- Sublimation: absorbing heat causes a solid to change directly into gas.
- Deposition: loss of heat causes gas to change directly into solid.
- Melting and freezing occur at the same temperature: melting and freezing point.
- Boiling and condensation occur at the same temperature: condensation and boiling point.
- The amount of energy that needs to be added or removed to change the state of a material is called latent heat.

When energy is added to a substance that is changing its state (for example, heating water that is boiling already), its temperature remains the same until all of the substance has changed state. If one draws a graph of the temperature of a substance as a function of the amount of heat given to it (see Figure 3), the phase changes show up as plateaus in the graph. The temperatures at which the phase changes occur vary greatly between different materials and depend on the type of substance.

Phases of Water

Water is one of the most important substances on Earth. It is a major component in the interaction between the Earth systems (hydrosphere, atmosphere, geosphere, and biosphere). It is also essential for life; liquid water is necessary in every environment on Earth that supports life forms, and may be necessary to any possible life forms elsewhere.

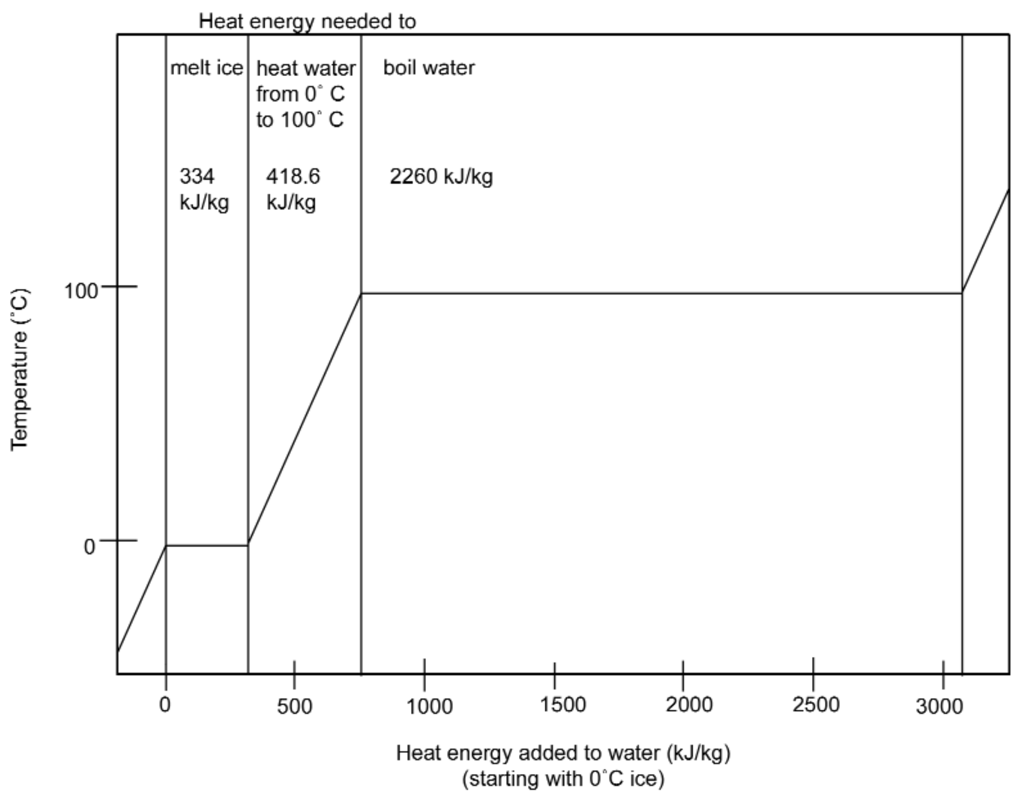

Figure 3. The heating curve of water shows the amount of energy needed to convert water from ice to liquid water and then to water vapor. Before ice reaches its melting point (0ºC; 32ºF), adding energy to it results in the increase of its temperature. While the ice is melting, its temperature stays at 0ºC (32ºF) until all the ice has melted, resulting in the first plateau in the curve. When more energy is added to the liquid water, its temperature increases, until the boiling point of 100ºC (212ºF) is reached. At this point, another plateau in the curve is created, as the temperature stays the same until all the water has turned into vapor. When more energy is added into water vapor, its temperature rises again. The curve can be read also right-to-left; in this case it describes the amount of energy removed from water when water vapor is turned to liquid and then to ice.

The three phases of water are ice or snow (solid water), liquid water, and water vapor or steam (gaseous water). All the phases of water have important roles in the Earth system: for example, liquid water from the oceans evaporates, forms into clouds, and later rains down on land, and may freeze into snow or ice deposits in cold areas. At normal atmospheric pressure, the melting (and freezing) point of water is 0˚C (32˚F), and the boiling (and condensation) point is 100˚C (212˚F).

The graph for the temperature change of water as a function of energy added to it (Figure 3) can be explained in the following manner. The temperature of ice, the solid form of water, is 0˚C or less. When ice is heated, its temperature rises as the heat energy is converted into the increased internal energy of the water molecules. This continues until the temperature of the ice reaches the melting point. At this point (also the zero point of the heat energy added to the ice in Figure 3), the heat energy given to the ice goes toward changing the phase of the water from ice to liquid – effectively breaking the solid bonds between water molecules - and does not show up as temperature change. This can be seen as the first plateau in the curve in Figure 3. Only when all the ice in the ice-water mixture has melted does the temperature in the (now liquid) water begin to rise again. The amount of energy required to melt the ice (the latent heat, sometimes also called "the heat of fusion") is 334 kJ per kg of ice. Additional energy given to the water after all the ice has melted results in a rise in the water temperature until the temperature reaches the boiling point, 100˚C. At this point, the energy given to the water goes into changing its phase from liquid into gas. During this process, the internal energy of the water molecules becomes so high that they overcome the forces keeping the water molecules together (such as attraction between molecules and the vapor pressure of gaseous water above the liquid), disassociate themselves from neighboring molecules, and become vapor. The amount of energy required to vaporize the water ("heat of vaporization") is 2260 kJ per kg of water. This creates the second plateau in the curve in Figure 3. As Figure 3 indicates, boiling 1 kg of water requires much more energy than melting the same amount of ice (or raising the temperature of the same amount of liquid water from 0˚C to 100˚C); this is because overcoming the forces keeping the liquid molecules together requires a lot more energy than breaking the solid bonds of ice.

The existence of the phase change plateaus is a source of misconceptions. People may think that the temperature of an ice-water mixture will rise when more heat is applied, even before all the ice has melted. When boiling water on the stove, if you turn up the burner, you will get a more vigorous boil, and people sometimes think that this means that the temperature of the water is rising. As explained above, this is not what happens in either case. The temperature of ice water will remain at 0˚C until all the ice has melted. When the water is boiling harder, it means that more water is being vaporized in a given time (the water in the pot boils faster), but not that the temperature is any higher. The additional energy given by the higher setting of the burner just goes into changing the phase of a larger amount of the water in a given time.

The total amount of energy required to cause a phase change can be written as an equation:

$$Q = m \times L,$$

where Q = heat energy (kJ),
m = mass (kg),
L = latent heat (kJ/kg).

Using the values given in Figure 2, the amount of energy needed to melt a given amount of ice or boil a given amount of liquid water can be calculated easily.

Keeping Heat at Bay

In order to keep items cool, we need to try and keep heat from interacting with them. The movement of heat from one place to another can be restricted by insulation: by keeping heat from entering or flowing out of an object. The word "insulation" can also be used to describe electric or acoustic insulation – keeping electric currents or sound from a certain place or within a certain place – but in this discussion, thermal insulation is the basic topic.

To combat the three ways in which heat can travel, there are three basic methods of insulation:

1) To fight conduction, some materials are used as insulators.
- E.g., many pots and pans have plastic or wood handles.

2) To fight convection, the space between hot and cold areas can be filled with "dead air."

- E.g., double-pane window: the layer of air between the outer and the inner windows stops the convection from transferring heat between them; narrow dead air space is better than wide since it makes the formation of convective air circulation currents more difficult.

3) To fight radiation, reflective or blocking materials can be used.
- E.g., reflective car sunshades placed against a windshield to prevent the inside of the car from heating up; sunscreen spread on skin to prevent sunburn.

Oftentimes, insulators are designed to combine different ways with which they can act to make them as efficient insulators as possible. For example, insulating material may be composed of poorly conducting material, have cell-like spaces to reduce the motion of cold or hot air, and be coated with reflective material. Insulation is used in homes and in various industrial applications, from steel furnaces to spacecraft.

Sunlight –The Principal Source of Energy on Earth

The Sun provides most of the energy on Earth. Some heat is generated inside the Earth, but it is a very small effect compared with sunlight. Without the Sun, the Earth would be cold and lifeless. The amount of solar radiation arriving on Earth at the top of the atmosphere is known as the solar constant, and is 1370 W/m^2. Much of the solar radiation arriving at Earth is reflected away or absorbed by the atmosphere, and typically only about half of it reaches the surface.

On Earth, the Sun's radiation is absorbed by the ground, the seas, and the atmosphere. It drives air flows in the atmosphere, currents in the oceans, and greatly influences climate and weather. It is the most important source of energy for life on Earth: it provides energy for photosynthesis and, in this manner, supports the first link in most food chains on Earth. It is possible for life to exist in places without sunlight (such as at the bottom of the oceans), but most of the life with which we are familiar uses the energy provided by sunlight in one way or another.

Shadows on Planets

The amount of solar radiation arriving at a point on the surface of the Earth varies between daytime and night-time. Roughly half of our planet is in sunlight at any given time (day), while the other half is shaded from the Sun by the Earth's own shadow (night). During the night, the energy of the sunlight no longer reaches the shadowed areas directly, and the surface is able to cool off by emitting infrared radiation into space. [Note that the surface emits infrared radiation also during the day, but the cooling effect is then countered by the arriving sunlight.] As a result, temperatures in a given place are usually lower during the night than during the day. Earth's dense atmosphere moderates the temperature variations and, under some weather patterns, the temperatures can actually be warmer at night than during the day.

The largest daily temperature differences on Earth occur in deserts. Deserts are hot because they are at low latitudes and, therefore, the Sun is almost directly overhead at noon for most of the year and, unlike rainforests at similar latitudes, they do not have the benefit of the cooling effect of substantial vegetation. Water vapor in the air can prevent infrared radiation from escaping into space, and the lack of it at desert areas means that they can cool efficiently at night. Under these conditions, the temperature difference between the day and the night can be about 40˚C (75˚F) (changing from 66˚C to 24˚C; 150˚F to 75˚F). The desert also provides a good example of the effectiveness of cooling by staying in the shadows: the temperature in the shadow of a desert rock can be more than 22˚C (40˚F) cooler than on top of it.

If we consider planets with no atmosphere or only a very tenuous atmosphere, the fluctuations in temperatures between the sunlit and shadowed sides of the planet can vary wildly. This is because the surface can heat up fast when it receives sunlight and also cool off quickly at night. For example, Mercury's atmosphere is very tenuous (virtually a vacuum) and cannot produce a similar moderating effect to Earth's. As a result, the daytime temperatures can be as high as 450˚C (850˚F), while at night, the temperatures can drop down to -180˚C (-300˚F).

MESSENGER and Shadows

The MESSENGER mission to Mercury is a great engineering challenge because of the high-temperature environment in which the spacecraft will operate. At Mercury's distance from the Sun, the solar radiation will reach levels 5-11 times as high as they are in space near Earth, depending on where Mercury is on its orbit around the Sun. Since the Earth's atmosphere allows only about half of solar radiation to pass through, the MESSENGER spacecraft will be exposed to as much as 22 times the amount of solar radiation as it would on the surface of Earth. Combined with the infrared radiation emitted from Mercury, this creates an environment for the spacecraft where temperatures can reach well over 400˚C (750˚F).

MESSENGER mission designers have developed several solutions to overcome this problem, such as using heat-resistant materials, and employing radiator panels to radiate the generated excess heat effectively into space. The spacecraft's orbit around Mercury has been designed so that its closest approach to the planet is away from the most sun-baked region of the surface and so that it flies quickly over the sunlit areas. This is achieved by an orbit where the periapsis (the closest point to the surface of Mercury and also the part of the orbit where the spacecraft's speed is at its highest; the distance from the surface is 200 km or 124 miles) is at a high latitude and the apoapsis (the farthest point of the orbit and also the part of the orbit where the spacecraft's speed is at its lowest; the distance from the surface is 15,193 km or 9443 miles) is far away from the surface of Mercury. This orbital design keeps the amount of infrared radiation received from the planet's surface at safe levels.

The central solution to the heating problem is the use of a sunshade made of cutting-edge thermal materials and designs. While the spacecraft is operating in orbit around Mercury, the sunshade will be pointed toward the Sun at all times, allowing the instruments to remain in its shadow. The temperature difference between the side of the sunshade facing the Sun and the shaded parts of the spacecraft can be as high as 400˚C (720˚F). As a result, MESSENGER's instruments will be in a thermal environment comparable to room temperature; during Mercury's orbit around the Sun, the temperature on the instrument deck of MESSENGER is expected to vary from a few degrees below 0˚C (32˚F) to 33˚C (91˚F).

The use of passive cooling methods is essential for the success of the MESSENGER mission. Using an active cooling system with refrigerants would be prohibitively expensive and probably not even technically feasible for a mission designed to study Mercury from orbit for one Earth year. The cost for the sunshade is about $130,000, which is very reasonable when considering its importance for the mission and that the total cost for the whole MESSENGER project (mission design, spacecraft construction, launch, mission operations, etc.) is about $300 million. An important consideration for minimizing the cost of the mission is to keep the spacecraft as lightweight as possible – each kilogram of mass increases the cost of launching the spacecraft significantly. Again, an active cooling system with refrigerants would increase the weight considerably, while the sunshade adds only 19 kg to the total spacecraft mass of 1100 kg. The total cost for the launch (including the launch vehicle as well as the services by the launch personnel) is about $65 million. Even though not all costs of the launch (such as the launch services) are directly proportional to the spacecraft mass, a rough estimate of the amount of money it costs to launch the spacecraft is $59,000 per kilogram, based on these numbers.

Another important aspect of shadows for the MESSENGER mission is the amount of sunlight reaching the polar regions of Mercury. Since Mercury's rotation axis is not tilted (as the Earth's is – that is why Earth has the kind of seasons that it does), the highest apparent position of the Sun in Mercury's sky at a given latitude on the surface does not change during Mercury's year. (But remember: the Sun does not actually revolve around Mercury; the rotation of the planet just creates the appearance that the Sun moves in the sky during the day.) For example, near Mercury's poles, the Sun appears very low near the horizon each day. In fact, right at the pole, the Sun appears to just crawl around the horizon every day, all year round, as the planet rotates. This means that the sunlight arriving at Mercury's polar regions arrives at a very low angle. Therefore, there probably are craters in the polar regions, whose bottoms have never seen sunlight, and it is possible for water ice to exist in these craters. (We say "water ice" to distinguish it from other kinds of ice made of different frozen materials.) Earth-based radar observations of Mercury have suggested that water ice might, indeed, exist in the polar regions, and confirming or rejecting this idea is one of the principal scientific goals of the MESSENGER mission.

LESSON PLAN: MEASURING THE EFFECTIVENESS OF SUNSHADES

In the activity at the heart of this lesson, students will construct a simple device to examine how substances can be protected from sunlight. They place an ice-water mixture in a coffee can and use a sunshade to protect the contents from sunlight. Based on the amount of ice that melts during the experiment (and their understanding that this is a way to measure how much heat energy the ice-water mixture receives), the effectiveness of their shade can be estimated. For a description of the experiment setup, see Figure S1 in Student Worksheet 1.

The experiment is done over two or three days. During the first day, the basic concepts of heat transfer and phase change are discussed, and the students form groups to design the sunshade to be used in their experiment. In the second day, the experiment is performed. In the third day, the results are analyzed. If there is sufficient time in the second day, the lesson can also be completed then.

The experiment serves two purposes: First, it is a simple way to test the effectiveness of a sunshade designed by the students. Second, the basic setup for the experiment is a simple way to measure the desired property – the effectiveness of the sunshade. But it also is intentionally designed to have some sources of error (such as heat conduction from warm air and sunlight striking and heating up the sides of the can, not just the top). While the errors are controlled in the experiment and the results about the effectiveness of the sunshades are valid, the students are also encouraged to think of ways to improve the design of the experiment to eliminate some of the sources of errors. (Sharing of data among different classes is also strongly encouraged.)

Materials

Per group of 3

- 2 11.5 oz. coffee cans
- Bucket to hold ice-water mixture
- Ice cubes or small chunks of ice (enough to fill the bucket and keep water cold)
- Water (enough to fill the bucket)
- Thermometer
- Shielding materials (each group brings their own)
- Stopwatch
- Stir stick (any stick that can reach the bottom of the bucket will do)
- Optional: Strainer
- Tape
- Standard ruler (30.5 cm, 12 inches)
- Calculator
- Protractor

Per class

- Scale capable of measuring at least 500 grams (one per class will do, but one per group is better)

Preparation

- Make enough copies of student worksheets and MESSENGER Information Sheet for each student to have one of each.

Points to consider in preparation of the experiment to ensure maximum results:

- It is best to conduct this experiment on a sunny day as close to noon as possible. This way the Sun's rays come more directly down on top of the cans and the energy received from the desired direction is maximized. The cooler the temperature is during the day, the smaller the errors due to heat conduction from the air. If you want to stress error control, you may want to conduct the experiment on a warm day. If you want to stress the shade effectiveness, you may want to perform the experiment on a cool (but sunny) day or in a cool classroom on a sunny day. If it is possible for students to choose at which time of the day to perform the experiment, you may encourage them to make the choice themselves.
- It is strongly encouraged that the students share their experiment data among different classes. The larger the data set on the variations in the experiment (time of day, angle of the sunlight striking the can, etc.), the better the students can understand the various sources of errors in the experiment and think of ways to eliminate them. If you do not have several classes with whom you can perform the experiment yourself, you may want to combine your efforts with another teacher.

Warm-up & Pre-assessment

1. Ask students to define temperature. Explain it to them in terms of the vibration of atoms and molecules.

2. Ask students the three basic ways in which heat and energy can be transferred. Ask students to think of examples of these ways, and record their answers. Group their answers into three categories, "Conduction," "Convection," and "Radiation." In each category, ask the students for ways in which each can be prevented (or insulated).

3. Focus on radiative heat transfer, especially sunlight. Ask students why we would want to prevent radiation, and which types need to be blocked (in particular, sunlight). Ask the students to list a few practical ways in which we can reduce or prevent exposure to radiation. Discuss active (cooling by doing work; refridgerators) versus passive (cooling without doing work; sunshades) cooling, and ask the students what they think are the advantages of each. (Be sure that cost efficiency is mentioned.)

4. Give the students the scenario in which they want to block as much sunlight as possible in order to prevent ice water from heating. Ask the students what (inexpensive) materials could be used to block the sunlight. Ask the students for ways in which the effectiveness of the materials can be tested. They may mention that they can take the temperature of the water to see how much energy has seeped through the shade, or they can add ice to the system and see how much melts.

5. Ask the students how they could take the information (such as how much ice melts) and come up with a specific amount of energy entering the system. Discuss the phase changes of water, and the idea of latent heat. Explain that a similar property, specific heat, relates to increasing the temperature of a substance without changing its phase. Discuss also the heating curve of water, and the meaning of the plateaus. Tell them that they will use this information to calculate the effectiveness of the sunshades they will design.

Procedures

Day 1: Shade Design (20-30 min)

1. Place students into groups of three. Hand out Student Worksheet 1, and briefly describe the setup of the experiment. Give students the rest of the class period to discuss and design the sunshade they will use in the experiment. Encourage them also to think of what time of the day they would like to perform the experiment (if it is possible for them to choose the time).

2. Remind the students that they need to build the shade as inexpensively as possible. The suggested cost cap is $5 but you may want to modify it or eliminate it altogether. Remind the students that they must fill out the design details segment in Worksheet 1 before building the shade in the next class, and that they will have 10 minutes to build their shades.

3. At the end of the class, remind the students to buy the materials (or bring them from home), keep the receipts, and bring everything to the next class, when the experiment will be performed.

Teaching Tip

If you do not want your students to have to pay for their materials, you may supply the materials yourself. Keep in mind, though, that they will be calculating the cost of their shades, so you need to provide a list of your material costs.

Day 2: Activity (45 min)

1. Have the students gather in their groups and assemble the shades. Allow a maximum of 10 minutes for assembly of the shades.

2. Have the students follow the instructions in Student Worksheet 2 to prepare and conduct the experiment.

3. Make sure the students are preparing two cans – one for control, one for the shade test.

4. While the students are waiting for ice to melt in their experiment devices, they should calculate the angle of the Sun in the sky and measure the angle of their devices from horizontal. Be sure that they bring a calculator with them to the experiment site to do this. If there is time, they could also begin working on the additional worksheets, or read the MESSENGER Information Sheet. You can also suggest to the students to discuss within their group heat transfer and what is happening to the ice-water mixture during the experiment. The students will consider these issues further in analyzing their results.

Teaching Tip

It is ideal to have the students start and stop their experiments at the same time, especially if they are doing the experiment outside. This way all of your students will be in the same location and will be easier to monitor. However, if you only have one scale for the entire class, it may be beneficial to have them start and finish in succession so that they do not have to wait to use the scale. If the students can weigh their ice immediately before and after it is put in the Sun, this ensures that the ice melts as a result of being exposed to the Sun, and not being exposed to warm air. You can do the weighing in succession by having Group One weigh their cans first (with and without ice), then move on to expose their device to sunlight (and start their stopwatch), then have Group Two weigh their cans, begin the experiment, etc. At the end of the experiment, Group One can stop the stopwatch, and weigh their ice first, and then Group Two does the same, etc.

Day 3: Analysis (45 min)

1. Have the students share the data on their experiments with other groups. If you had different classes perform the experiment, share the other classes' data.

2. Have the students perform their analysis in Student Worksheets 2-3. This can also be given as homework once the students have the data from the other classes.

Discussion & Reflection

1. Discuss results with students. Was it what they expected, what was their final cost-efficiency (expressed in terms of the percentage of energy blocked by the sunshade versus the cost of the sunshade, %/$, on Page 4 of Student Worksheet 2), whose design was the most cost-efficient, what materials did they use, etc.

2. Remind the students of the heat curve of water, and ask how that is important to the experiment. How would the experiment be affected if phase changes did not occur this way?

3. Discuss with students the possible sources of error in the setup of the experiment and modifications they may have made for the setup on Student Worksheet 2. If they want to re-do their experiments, encourage them to do so. Later they can compare whether their cost-efficiency improved as a result. (Since a control can is used in both cases to take errors into account, the change should not be significant if the sunshade design is efficient.) Discuss the importance of understanding sources of errors in scientific experiments and the need to improve designs and repeat experiments as errors are discovered.

4. Remind the students of the idea of passive versus active cooling, and relate it to the concept of shadows. Discuss with students the idea of shadows creating night-time on planets, and the resulting change in temperature between night and day. Discuss how atmospheres play a role in distributing and balancing night and day temperatures.

5. Discuss the MESSENGER mission to Mercury and why it needs a sunshade. Hand out the MESSENGER Information Sheet (if you have not done so already). You can have the students consider the MESSENGER mission in greater detail by giving them an Internet research project to examine the passive cooling methods used by the MESSENGER mission designers. You can instruct the students to pay special attention to the design of the sunshade and what kind of materials are used in its construction, as well as what is known about the possibility of ice in the shaded craters in Mercury's polar regions.

Lesson Adaptations

Constrain the parameters of the experiment in the activity further by limiting the total weight of the experiment device (coffee can, shade, and whatever modifications the students make to the basic setup).

Extensions

- Have the students design actual heat shields that could be used in NASA missions to hot environments. They can research the materials and designs already in use and come up with their own. They can figure out ways to minimize the cost for these shields based on their research.

- The Student Challenge Worksheet examines the process of ice melting to water in the experiment in terms of entropy, including a calculus-based mathematical discussion of it. Even though a comprehensive discussion of entropy would be more appropriate in college, you may want to challenge at least some of your students to become acquainted with the concept.

Curriculum Connections

- *Physics:* Have students research the more exotic phases of matter (which only occur at very high or low temperatures): plasmas, superfluids, superconductors, Bose-Einstein condensates, and quark-gluon plasmas.
- *Chemistry:* Have students find out how and why water behaves differently than most materials when it changes physical states. (For example, water expands as it freezes, contrary to other liquids.) They can discuss the structure of the water molecule and how it changes when heat is added or removed.
- *Life Science:* Students can research the effects of water's structure on life. For example, if water did not expand as it freezes, ice would not float on top of liquid water due to their relative densities. This would have a major impact on anything living in lakes that have their surfaces freeze in the winter. Also, students can discuss why scientists think that liquid water is essential to life and why astronomers looking for life elsewhere think they must first find liquid water.

Closing Discussion

Remind students that by having learned about basic properties of heat and energy transfer, they are now able to design ways to keep items comfortable in excess sunlight (or other hot environments). They also are able to recognize that scientific experiments may sometimes have sources of error resulting in a need to modify and re-do the experiment. Ask students why they think it is important to maximize the cost-efficiency when designing real-life applications. Discuss the importance of cost-efficiency for NASA missions. Discuss the MESSENGER mission to Mercury and why it needs a sunshade. If you had students participate in the Internet project, you can discuss their results here.

Assessment

You can use Page 3 of Student Worksheet 1 describing the students' design of the experiment and shade, Pages 2-7 of Student Worksheet 2 for assessment, as well as the Student Challenge Worksheet.

Internet Resources & References

MESSENGER website

http://messenger.jhuapl.edu

Astrobiology Magazine article "Water: The Molecule of Life"

http://www.astrobio.net/news/article453.html

Department of Energy: Fact sheet on home insulation

http://www.ornl.gov/roofs+walls/insulation/ins_01.html

National Insulation Association

http://www.insulation.org/

U.S. Geological Survey: Water Science for Schools

http://ga.water.usgs.gov/edu/

National Science Education Standards

http://www.nap.edu/html/nses/html/

American Association for the Advancement of Science, Project 2061 Benchmarks

http://www.project2061.org/tools/benchol/bolframe.htm

Measuring the effectiveness of sunshades

In this experiment, you will measure how effective a sunshade is in protecting an ice-water mixture from melting in sunlight. Consider some of the physics in this experiment:

▼ Heat transfer: heat passes from one substance or an object to another by:

1) Conduction
   - Heat is transferred through material without any of the material moving.
2) Convection
   - Heated material moves and carries heat with it.
3) Radiation
   - Energy from heat is transmitted via electromagnetic radiation (e.g., infrared rays) – either through a medium (such as air) or without need for intervening material (such as through vacuum).

▼ Insulation: To combat the three ways in which heat can travel, there are three basic methods of insulation:

1) To fight conduction, some materials are used as insulators (a material with a small thermal conductivity is a poor heat conductor and therefore a good insulator).
2) To fight convection, the space between hot and cold areas can be filled with "dead air."
3) To fight radiation, reflective or blocking materials can be used.
   - E.g., reflective car sunshades, sunscreen used to prevent sunburn.

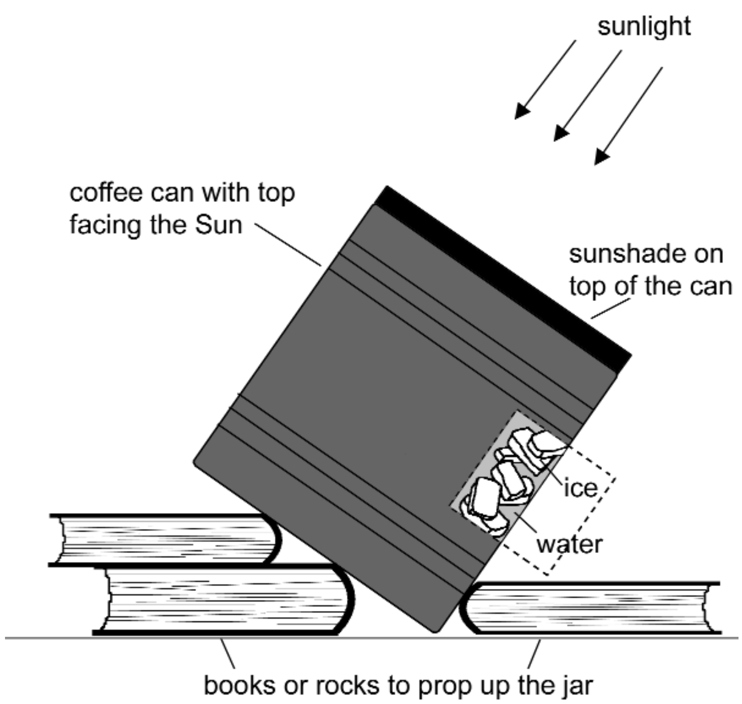

Figure S1. Setup for the experiment measuring the effectiveness of sunshades. A coffee can is filled with an ice-water mixture (see cut-away box in picture). A shade is placed on top of the can, and the device is placed in sunlight. By measuring the amount of ice melted by the sunlight, the effectiveness of the shade can be calculated.

Procedures:

1. As a group, examine the basic setup for the experiment (Figure S1). Decide among yourselves what sort of (inexpensive) materials would make the best sunshade. Keep in mind that you want to minimize your cost. Draw your design on Page 3 of this worksheet.

2. Design a plan for your coffee can shade, including a design drawing, a list of materials needed and their estimated cost (not to exceed the assigned cost cap), and a brief explanation as to why your group thinks your shade will succeed. Record this information and create a design for your shade on Page 3 of this worksheet. The final result of the experiment will be the cost-effectiveness of your sunshade: you must design as effective a shade as possible as inexpensively as possible.

3. Decide who in the group will buy which materials, and bring the shading materials with you to class on the day you do the activity. Keep your receipts so that you can later calculate the cost-efficiency of your shade. If you bring supplies from home, find out how much they cost at a store or on the Internet.

Team Members: ______________________________

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____

____

Sunshade Design

List of materials, with cost for each (fill in the cost after you have bought the materials):

Explain why you think the shade design will work well:

Sunshade Design drawing

The scale of your drawing: ____________

MEASURING THE EFFECTIVENESS OF SUNSHADES

Materials

- ▼ 2 11.5 oz. Coffee cans
- ▼ Bucket to hold ice-water mixture
- ▼ Water and enough ice to fill the bucket and keep water cold
- ▼ Thermometer
- ▼ Stopwatch
- ▼ Stir stick
- ▼ Strainer (optional)
- ▼ Tape
- ▼ Standard ruler (30.5 cm, 12 inches)
- ▼ Calculator
- ▼ Scale
- ▼ Protractor

You will now test your sunshade design.

1. Get in your groups and gather materials needed. If your shade requires assembly, do that now.

2. Fill a bucket almost to the top with ice. Add cold water until it covers the ice. Put the thermometer in the water and wait until the temperature reads 0°C. You may need to stir the ice water a couple of times to ensure that the water is the same temperature throughout the bucket. (Be sure that you use a stir stick and not the thermometer to stir.)

3. For this experiment, you will have two coffee cans: one will be the control, with no lid, and the other will use your sunshade. Label one can "Control" and the other "Shade."

4. Weigh the coffee cans on the scale. Fill the control can about one-third of the way with ice, and weigh again. Record these values on Page 3. Repeat for the shade can. (It is not necessary to have exactly the same amount of ice in each can.)

5. Fill each coffee can with water from the ice bucket about two-thirds full, making sure the water covers the ice. Be careful to not get extra ice into the can.

6. Attach your shade to the top of the can labeled "Shade."

7. Bring the cans to the experiment site (quickly, to ensure that the ice melts as a result of the sunlight, and not the time it sits at room temperature). Prop the cans so that the tops are facing the sunlight. Refer to Figure S1 of Student Worksheet 1 for the set-up design. Start the stopwatch.

WARNING

Do *not* look directly at the Sun!

Looking for even a few seconds can cause permanent damage to the eyes! Note that sunglasses do *not* provide an adequate safeguard against looking directly at the Sun.

So remember to ***never* look directly at the Sun!**

Name ______________________________

8. Check your control every 10 minutes. While you are waiting for the ice to melt, you can measure the angle of the Sun in the sky and the angle of your cans, steps 9 and 10 below.

9. Measure the angle of the position of the Sun in the sky. To do this, stand a 30.5-cm (12-inch) ruler up straight with the short edge flat on the ground. With a meter stick, measure the length of its shadow in centimeters. Refer to Figure S2 as you make your calculations.

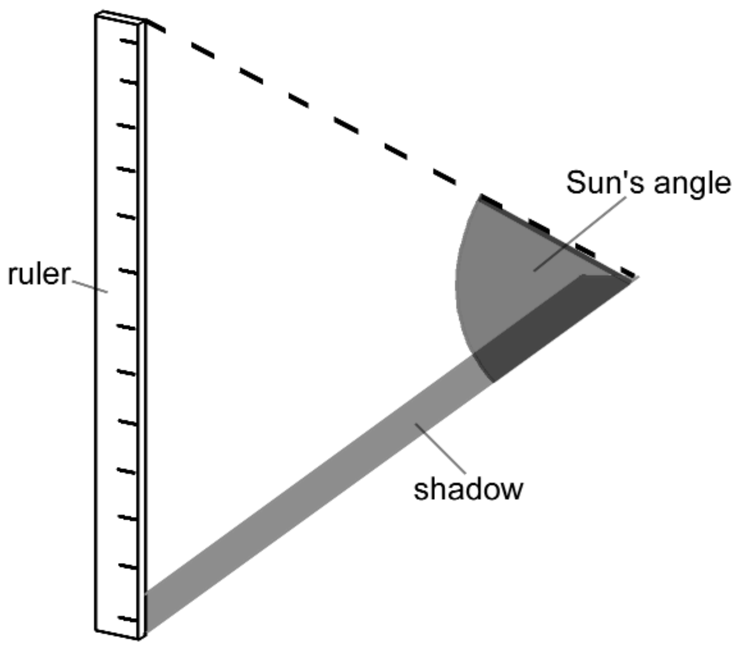

Figure S2: Calculating the Sun's angle.

Measured shadow length:

____________________ cm

tangent $\phi = 30.5$ cm / x

Where ϕ is the Sun's angle in the sky, and x is the length of the shadow that you measured (in centimeters).

Therefore,

$\phi = \arctan [30.5 / x]$

$\phi =$ ______________ degrees

10. Measure the angle that your cans are inclined (α) using your protractor.

$\alpha =$ ______________ degrees

11. When about one-third of the ice in the control can appears to have melted (or 30 minutes has passed, whichever comes first), remove both cans from the Sun and stop the stopwatch. Remove the sunshade from the can, and pour the water out of the can so that only the ice remains. You can use a strainer placed on top of the can when you remove the water, to make sure the ice remains inside. Weigh the can with ice. Remove ice from the can and weigh the empty can again. Record your results in the chart. Repeat with the control can.

Record your results here.

Time of the day when you performed your experiment: ____________

Angle of the Sun in the sky (from horizontal): ____________

Angle of can (from horizontal): ____________

Cost of shade: $ ______________________________

In the beginning:

Control can:

- Diameter of coffee can top: ____________ cm
- Weight of empty coffee can: ____________ g
- Weight of can with ice (without water): ____________ g
- → Difference (Weight of ice): ____________ g

Can with shade:

- Weight of empty coffee can: ____________ g
- Weight of can with ice (without water): ____________ g
- → Difference (Weight of ice): ____________ g

In the end:

Time used for the experiment: ______________________ seconds

Control can:

- Weight of can with ice (without water): ____________ g
- Weight of empty coffee can: ____________ g
- → Difference (Weight of ice): ____________ g

Can with shade:

- Weight of can with ice (without water): ____________ g
- Weight of empty coffee can: ____________ g
- → Difference (Weight of ice): ____________ g

Calculating the energy used in melting the ice:

The total energy required to melt ice is given by the equation:

$$Q = m \times L$$

where Q = heat energy (kJ)

m = mass (kg)

L = latent heat (kJ/kg)

Latent heat ("heat of fusion") of water ice: 334 kJ/kg

Surface area of coffee can lid: ____________ m^2

Use your measurements and the equation above to fill in the table below:

	Shade can	Control can
Mass of ice melted (kg)		
Amount of energy used (kJ)		
Energy/time used (J/s)		
Energy/s/unit area ($J/s/m^2$)		

Use the Energy / time to calculate what percent of the energy your shade kept away from the ice-water mixture:

What is your cost-efficiency (the percentage of energy kept away from the shaded mixture versus the cost of the shade)? (Your units should be %/$)

Interpreting the results

1. How was your coffee can angled with respect to the arriving sunlight? (This is the difference between your measured α and ϕ values.) How do you think it affected your experiment?

2. Why did you have to weigh the can before the experiment as well as after? Were your results different? Why or why not?

3. Why do you think the control can is useful? (Name at least two reasons.)

4. Why is the cost of the shade so important? Think of real-life examples where you might want to minimize the cost of a sunshade.

5. What sources of error might you have?

6. The solar constant (the amount of solar energy received by Earth) on top of the atmosphere is about 1370 $J/s/m^2$. The atmosphere reflects away or absorbs 30-50% of the radiation (depending on the cloud cover), so that the typical amount of solar radiation arriving on the surface of Earth is 700-1000 $J/s/m^2$.

a) How does the amount of energy used in melting the ice in the control (unshaded) can in your experiment compare with the solar radiation?

b) How could you explain the similarities or differences in your value based on the experiment design?

8. Scientists often have to revise their experiments after an initial try when they discover possible sources of errors and must eliminate them. How would you conduct your experiment differently if you had to do it again? Why?

9. Would you construct your shade differently if you had to do the experiment again? Why or why not?

If you would like to improve on the experiment design, describe your modifications and draw a scaled design of the new experiment setup on Page 7 of this worksheet.

Team Members: ______________________________

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Modified Experiment Design

Describe how you plan to modify the basic experiment setup described in Figure S1 in Student Worksheet 1:

____

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Explain why you think this experiment setup will work better:

____

____

____

____

____

Design drawing for your modified experiment setup

The scale of your drawing: __________

Entropy in Your Coffee Can

Scientists use the term entropy to describe the amount of disorder or randomness in a substance at a molecular level. Entropy is important in the science of thermodynamics, which is the study of the relationships between various forms of energy, such as heat and mechanical work. There are three basic laws of thermodynamics:

1) Energy may change form (e.g., from chemical energy to mechanical energy in a car gasoline engine), but it is never created or destroyed ("conservation of energy").
2) Heat energy flows from hotter to colder substances unless work is done..
3) There is a theoretical temperature where matter would have the least possible internal energy and no disorder. However, it is impossible to reduce the temperature of any system to this temperature, called absolute zero, 0 K (-273°C, -459°F).

The second law indicates that on its own accord, heat will flow only from a hotter material to a cooler one, and not vice versa. Heat flowing into cool material will increase the entropy of the material by causing the motion of its atoms and molecules to become more disorderly. As a result, the temperature of the cool material rises; or, if a solid material is at melting temperature, the solid bonds between molecules break – the solid material melts.

It is possible for entropy to decrease in a substance, but this is offset by increasing entropy in a connected substance. For example, when a pond of water freezes, its entropy decreases, but the thermal energy released by the freezing process increases the entropy of the surrounding air, resulting in a positive change of entropy for the entire ice-pond-surrounding-air system.

1. Think about the experiment you performed with ice melting in the coffee can.

a) Explain what happened to the motion of and bonds between the ice molecules.

____

____

b) How can you express this in terms of entropy?

____

____

c) What about the water that was there at the beginning of the experiment? Did its entropy change? How did it change?

____

____

d) What happened to the total entropy in your classroom (or in the universe!) as a result of this experiment? Did it increase or decrease? Why? ____________________________________

____

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Name ____________________________________

The change of entropy in thermodynamic processes can be expressed mathematically. To calculate the entropy change between two thermodynamical states, you first find a reversible path between them. (Reversible path is one which you can really reverse: for example, to change ice to boiling water, you first melt the ice and then heat the water; you do not just suddenly change the ice to boiling water.) A change in entropy is defined as the reversible heat flow q (change in thermal energy) divided by the temperature at which the heat flow occurs (T):

$$\Delta S = q/T,$$

To calculate the total change in entropy when changing from thermodynamical state A to B, you integrate to get the total change in entropy:

$$\Delta S_{A \to B} = \int_A^B \frac{dq}{T}$$

For a phase change, the change in thermal energy is:

$$q = \Delta H,$$

where ΔH is the change in the heat content (also called "enthalpy ") of the substance. For example, to melt ice, ΔH is the latent heat times the mass of the melted ice.

Note that the sign of the entropy change determines whether entropy is gained or lost in that part of the system.

1. What is the change in entropy for the amount of ice that melted in your shaded can? Is the change positive or negative?
[Hint: $\Delta S = \Delta H / T$, and now ΔH = 334 kJ/kg x (mass of melted ice)]

2. The amount of solar energy arriving on top of the atmosphere of Earth is 1370 $J/s/m^2$ (= the solar constant). That is, in one second, 1370 J of energy arrives from the Sun per square meter of Earth's atmosphere on top of the atmosphere. How much does the entropy change in transferring that amount of thermal energy for the Sun? The Earth? The Earth-Sun system? [Hint: The temperatures of the Sun and Earth do not change appreciably during the process, so that $\Delta S = q/T$]

3. Heat is a form of energy. The amount of energy required to melt the ice (the latent heat) is 334 kJ per kg of ice. We can compare this amount of energy with the amount of potential energy released when a 1 kg block of ice is dropped from a certain height. How high would you have to drop the block of ice in order for it to release the same amount of energy required to melt it? [Hint: The potential energy, PE, of a system is given by the equation PE = mgh, where m is the mass of the object, g is the gravitational acceleration of the Earth, and h is the height of the object.] [Note that this question does not have to do with entropy but is a neat way to compare different forms of energy.]

<u>Constants you need:</u>

Latent heat of water ice = 334 kJ/kg

Temperature of the Sun = 5800 K

Temperature of the Earth = 288 K

Gravitational acceleration of the Earth = 9.8 m/s^2

Answer Key

Student Worksheet 1

Materials, cost, and design will vary (but make sure that the students did not purchase materials the total cost of which is over the assigned limit).

Students Worksheet 2

Page 3

Answers will vary. You can check the students' calculations to make sure the "Weight of ice" is "Weight of empty coffee can" subtracted from "Weight of can with ice."

Page 4

	Shade can	Control can
Mass of ice melted (kg)	mass	mass
Amount of energy used (kJ)	mass x 334	mass x 334
Energy/time used (J/s)	energy/1000/time on page 3	energy/1000/time on page 3
Energy/s/unit area (J/s/m^2)	above line/surface area	above line/surface area

What percent of the energy does your shade keep away from the ice-water mixture?

(Energy/time (Control)) – (Energy/time (Shaded)) / (Energy/time (Control)) Even a simple shade (such as the coffee can lid) reduces the energy used by at least 10%. Better designs should do a considerably better job.

What is your cost efficiency? (Your units should be %/$)

Number in above line / cost on page 3. If the cost of the coffee can lid is estimated at 50 cents, the cost-efficiency using the 10% reduction would be 20%/$. For a 90% reduction using a $2 shade, the cost-efficiency would be 45%/$. The answers will vary considerably based on the design.

Page 5-6

1. How was your coffee can angled with respect to the arriving sunlight? How do you think it was beneficial or detrimental for your experiment?

The best way to set up the coffee can with respect to the Sun is to point it so that its top is as perpendicular as possible to the arriving sunlight (or the can and the direction of the sunlight are as parallel as possible – i.e., the measured angles are the same). This ensures that the shade blocks the most sunlight from hitting the can. Otherwise sunlight coming at an angle could heat up the sides of the can and transfer heat to the water through conduction.

2. Why did you have to weigh the can before the experiment as well as after? Were your results different? Why or why not?

Weighing the cans with ice vs. cans without ice is also the best way to measure the mass of the ice quickly. After the experiment, the cans will have a few remaining water droplets on the insides. Though there would not be very much, it may mean the difference of one or two grams, which could affect the results of the experiment. Individual results may vary.

3. Why do you think the control can is useful? (Name at least two reasons.)

Examples of good answers: The control tells us when enough ice has melted without having to remove the shade, and provides an estimate of how much the experiment is affected by various error factors (e.g., heat conduction from the environment, variations of the amount of sunlight lost in the atmosphere due to local conditions such as clouds, humidity, weather, etc.). This makes the calculation of the efficiency of the shades more accurate.

4. Why do we care how much the shade costs? Think of real-life examples where you might want to minimize your shade cost.

Answers may vary. We care how much the shade costs because there are real-life applications, and we always want to minimize our costs in real life. Examples may include NASA missions (like MESSENGER), or every-day examples like hikers or farmers or people or things that may need to be out in the sunlight for long periods of time.

5. What sources of error might you have?

Answers will vary. Possible answers include heat conducted to the can from the environment, additional ice melting as a result of having time between measurements and start/stop of stopwatch, etc.

6. The solar constant (the amount of solar energy received by Earth) on top of the atmosphere is about 1370 $J/s/m^2$. The atmosphere blocks 30-50% of the radiation (depending on the cloud cover), so that the typical amount of solar radiation arriving on the surface of Earth is 700-1000 $J/s/m^2$.

a) How does the amount of energy used in melting the ice in the control (unshaded) can in your experiment compare with the solar radiation?

In the basic setup of the experiment done in roughly room temperature, the energy used is a lot more (even more than twice as much) as the real value of the solar constant. Under different conditions, the calculated value might be close to the actual value, but probably still somewhat higher.

b) How could you explain the similarities or differences in your value based on the experiment design?

There is additional heat coming into the can to melt the ice besides solar radiation. The most significant source is heat conduction from outside, either from warm air around the experiment device and/or sunlight striking the sides of the can. This question is used to prompt the students into thinking heat conduction as a significant source of errors and perhaps improving on their design of the experiment based on this realization if they were to perform the experiment again.

8. Scientists often have to revise their experiments after an initial try when they discover possible sources of errors and must eliminate them. How would you conduct your experiment differently if you had to do it again? Why or why not?

Answers will vary. For example, they could tilt the device more toward the Sun to eliminate sunlight striking the sides of the can, they could conduct the experiment more quickly, they could place the device in a cool, insulated container to reduce the level of heat conduction through the sides of the can, etc.

9. Would you construct your shade differently if you had to do the experiment again? Why or why not?

Answers will vary. The students may say they want it to cost less, use better materials, etc.

Page 7

Describe how you plan to modify the basic experiment setup described in Figure S1 in Student Worksheet 1. Explain why you think this experiment setup will work better.

Note that the idea behind asking the students to consider modifying the experiment setup is that the way the system is set up in Figure S1, heat conduction from the warm environment in which the coffee cans sit will be a source of errors in the experiment. The presence of the control can is needed to keep track of these errors. Possible modifications of the setup include performing the experiment as close to noon as possible so that the sunlight enters only through the shade and does not warm the sides, encasing the device in a cold environment (e.g., thermal lunch bag filled with ice), performing the experiment on as cold a day as possible with sufficient sunlight still present, etc. These answers have been considered in Question 8 on Page 6; here the ideas are put in the form of an actual improved design.

Student Challenge Sheet

Page 1

1. Think about the experiment you performed with ice melting in the coffee can.

a) Explain what happened to the motion of and the bonds between molecules of the ice.

The thermal energy received by the ice resulted in the breaking of the solid bonds between the ice molecules. As a result, their motion became more disorderly.

b) How can you express this in terms of entropy?

The entropy of the ice increased.

c) What about the water that was there at the beginning of the experiment? Did its entropy change? How did it change?

Since the thermal energy received by the contents of the coffee can went to the melting of the ice, and the temperature of the water did not increase, its entropy did not increase.

d) What happened to the total entropy in your classroom (or in the universe!) as a result of this experiment? Did it increase or decrease?

The total entropy increased. This is the result of all natural processes.

Pages 2-3

1. What is the change in entropy for the amount of ice you melted in your shaded can?

Answers will vary. A sample answer if mass of melted ice = 100 g

$\Delta S = \Delta H / T$

now ΔH = 334 kJ/kg x (mass of melted ice)

$\Delta S = \Delta H / T$ = 334 kJ/kg x 0.100 kg / 273 K

= +0.122 kJ/K = + 122 J/K

The sign of the entropy change is positive: entropy increased in the ice.

2. How much does entropy increase when transmitting 1370 J of energy from the Sun to the Earth?

The temperatures of the Sun and Earth do not change appreciably during the process, so

$\Delta S = q/T$,

and therefore

ΔS_{Sun} = - 1370 J / 5800 K = - 0.236 J/K (minus sign because Sun emits energy)

ΔS_{Earth} = + 1370 J / 288 K = +4.757 J/K (plus sign because Earth gains energy)

The total change of entropy for the Sun-Earth system is

$\Delta S_{Sun+Earth} = \Delta S_{Sun} + \Delta S_{Earth}$

= - 0.236 J/K + 4.757 J/K

= + 4.521

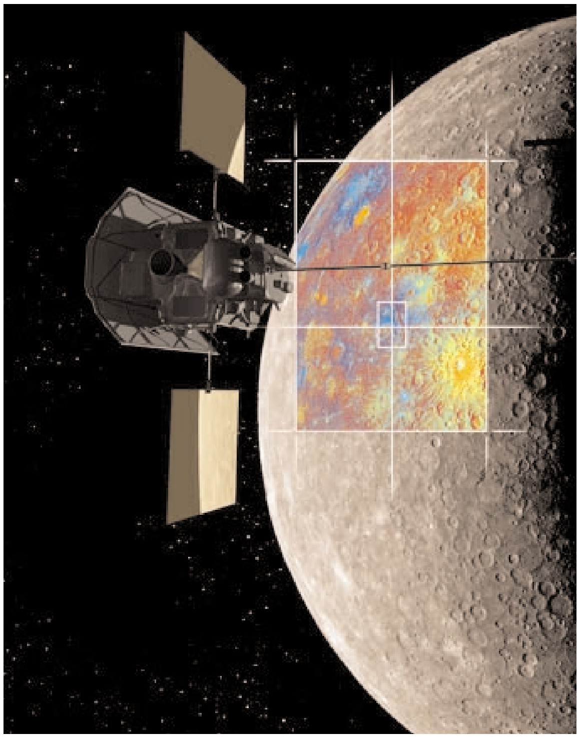
and the sign is positive – entropy increases in the process, as expected!

3. Potential energy PE = mgh

1 kg x 334 kJ/kg = 1 kg x 9.8 m/s^2 x h

h = 34,000 meters = 34 km

MESSENGER INFORMATION SHEET



The MESSENGER Mission to Mercury

MESSENGER is an unmanned U.S. spacecraft that will be launched in 2004 and will arrive at the planet Mercury in 2009, though it will not land. Instead, it will make its observations of the planet from orbit. MESSENGER will never return to Earth, but will stay in orbit around Mercury to gather data until sometime in 2010.

MESSENGER is an acronym that stands for "**ME**rcury **S**urface **S**pace **EN**vironment, **GE**ochemistry and **R**anging," but it is also a reference to the name of the ancient Roman messenger of the gods: Mercury, after whom the planet is named.

MESSENGER will be only the second spacecraft ever to study Mercury: In 1974 and 1975 Mariner 10 flew by the planet three times and took pictures of about half the planet's surface. MESSENGER will stay in orbit around Mercury for about one Earth-year; its close-up observations will allow us to see the whole planet for the first time.

Sending a spacecraft to Mercury is extremely complicated. The planet is very close to the Sun; it moves very fast in its orbit, and intense radiation and heat can cause catastrophic consequences. Therefore, engineers and scientists have planned the mission carefully. They have found ways to protect the spacecraft against radiation, and they have built safeguards to make sure it can operate reliably in the difficult Mercurian environment.

During its mission, MESSENGER will attempt to answer many questions about the mysterious planet. How was the planet formed and how has it changed? Mercury is the only rocky planet besides Earth to have a global magnetic field; what are its properties and origin? Does ice really exist near the planet's poles? Answers to these scientific questions are expected to hold keys to many other puzzles, such as the origin and evolution of all rocky planets. As we discover more, we expect that new questions will arise. You could be the one answering many of these new questions!